

Heliospheric plasma sheet and coronal streamers

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Abstract. In-situ measurements of solar wind plasma and magnetic field between 0.3 and 1 AU are used to investigate the structure of the heliospheric plasma sheet, namely the region of enhanced plasma density that surrounds the heliospheric current sheet. The boundaries of the plasma sheet generally appear well defined. In agreement with previous observations at 1 AU, the plasma sheet thickness is much larger than that of the embedded current sheet. Interplanetary observations are compared with those at coronal streamers near 0.1 AU based on radio occultation measurements. It is concluded that the coronal counterpart of the plasma sheet is the stalk of coronal streamers observed in white-light measurements. Beyond 0.1 AU the heliospheric plasma sheet appears to be a permanent density structure that expands with the solar wind without significant evolution.

Introduction

The heliospheric plasma sheet (HPS) is a region of enhanced plasma density that surrounds the heliospheric current sheet (HCS). This is a surface rooted on the near-equatorial belt of coronal streamers and extending into the interplanetary space to divide the heliosphere into two regions of opposite magnetic polarity.

The HPS structure near 1 AU has already been the object of several investigations [e.g., *Borrini et al.*, 1981; *Gosling et al.*, 1981; *Winterhalter et al.*, 1994; *Huddleston et al.*, 1995; *Crooker et al.*, 1996]. At this distance from the Sun, however, the density enhancements associated with the heliospheric plasma sheet are often difficult to distinguish from those due to stream interaction regions. This masking effect becomes less important closer to the Sun, since there the effects of the dynamical interaction between slow and fast solar wind flows are less developed.

With the goal of obtaining clean observations of the plasma sheet we have then analysed in-situ solar wind measurements by Helios 2 inside 1 AU at time intervals encompassing HCS crossings. 81-s averages of the ion (protons and alpha particles) density, velocity, and temperature and of the interplanetary magnetic field have been used. The investigated time interval corresponds to the first aphelion-to-perihelion phase of the mission, with the spacecraft travelling from 1 to 0.3 AU in approximately four solar rotations. This interval is close to a minimum of the solar activity cycle, hence characterized by a low-latitude and low-inclination current sheet.

In an attempt at obtaining a comprehensive view of the phenomenon, plasma sheet observations in interplanetary space are related to radio occultation measurements of low latitude coronal streamers near the Sun. The stalk of coronal streamers observed in white-light measurements is found to be the coronal counterpart of the heliospheric plasma sheet.

The plasma sheet between 0.3 and 1 AU

Figure 1 shows an example of solar wind protons and magnetic field observations in correspondence of HCS crossings near the Sun (at about 0.3 AU). Data are plotted versus the spacecraft Carrington longitude (CL), increasing from right to left (with time increasing from left to right). At the left lower corner the range in heliocentric distance is indicated. From top to bottom the different panels display: V , proton bulk velocity (km s^{-1}); ϕ , magnetic field longitude (degrees, solar-ecliptic coordinates); N , proton density (cm^{-3}); δN , density variation per time unit ($\text{cm}^{-3} \text{ s}^{-1}$); $\delta N/N$, relative density variation per time unit (s^{-1}); T , proton temperature ($10^3 \text{ }^\circ\text{K}$); B , magnetic field magnitude (nT); P , total (proton thermal plus magnetic) pressure ($10^{-9} \text{ dyn cm}^{-2}$); β , ratio of thermal to magnetic pressure. δN is the rms value at four data points (324 seconds) of the time derivative of N , as given by the difference between consecutive density values divided by the sampling time (81 seconds). $\delta N/N$ is obtained by dividing δN by the density averaged over 324 seconds. The computation of δN and $\delta N/N$ based on Helios measurements is similar to that used in the radio occultation measurements except for differences in sampling rate and averaging period. The sampling rate of the Doppler data referred to in the following section is one per 10 seconds while the period over which scintillation is estimated is 180 seconds, hence smaller scale structures.

The main polarity reversal in Figure 1 is near CL 310, where a net change of about 180° in the field longitude ϕ occurs. A strong density enhancement (plasma sheet) is seen to encompass the current sheet crossing. The plasma sheet, with an angular width of 1.6° , appears to be much wider than the magnetic transition (in agreement with observations by *Winterhalter et al.* [1994] near 1 AU). Density fluctuations become stronger at the plasma sheet. However, in terms of relative amplitude ($\delta N/N$) there is no relevant change with respect to the ambient values. In addition to the one mentioned, other complete or partial crossings of the HCS are observed in the examined period, always accompanied by an enhancement in density. These multiple crossings

are probably due to a wavy structure of the current sheet and/or to fluctuations in its motion with respect to the spacecraft, although more complicated geometries (e.g., flux ropes, see [Crooker *et al.*, 1996]) cannot be ruled out. The density bumps observed in connection with the HCS crossings are embedded in a density halo, a region with slightly higher density than observed at larger distance from the current sheet. All these structures do not appear affected by stream interaction effects. In fact, due to the small heliocentric distance, a definite interaction region in front of the incoming high-speed stream (on the right in Figure 1) has not developed yet, as seen from the behavior of parameters like density, temperature, magnetic field intensity, and pressure. This confirms the advantage of using observations at small heliocentric distance to study the HPS structure.

Another example of HCS crossing at small heliocentric distance is given in Figure 2. A clear and strong density enhancement is observed in correspondence of the magnetic polarity reversal (near CL 150). The density bump has an angular width of 1.2° , while the density halo is seen to extend to about 15° . This plasma sheet observation is very clean, in no way perturbed by the small high-speed stream starting at CL 144.

At the time of the examined Helios observations (first months in 1976) the interplanetary pattern was very stable. This makes meaningful a comparison between observations near the Sun and near 1 AU. With reference to the period shown in Figure 1, we report in Figure 3 the observations for the corresponding (in terms of Carrington longitudes) current sheet crossing two solar rotations in advance, when the spacecraft was close to 0.9 AU. The overall pattern emerging from this figure is quite similar to that in Figure 1, with strong density bumps localized at the field reversals and an extended density halo. An exception is represented by a double polarity change around CL 270, for which there is no evidence of HPS. We believe that this is due to the fact that in this case we are going through a single filament of different polarity rather than through the heliospheric current sheet. A further remark is about a tiny

high-speed stream and interaction region observed at approximately 259-256 CL (see, in particular, signatures in temperature and pressure). Another weak velocity enhancement is observed at 249-246 CL. Thus, in addition to the fast wind stream associated with the large compression region at Carrington longitudes 242-229, other weaker high-speed streams are seen to exist, mixed with the plasma sheet encounters. This confirms the difficulty in getting clean plasma sheet observations near 1 AU.

The main conclusion drawn from Figures 1 to 3 is that the HPS structure does not vary significantly with the heliocentric distance in the region from 0.3 to 1 AU. The plasma sheet has well defined boundaries. The proton density is seen to increase of a factor of 2-3 with respect to the ambient value. The resulting angular width for clean crossings of the plasma sheet is 1-2 degrees. Broader events are probably due to the corrugated shape of the sheet and to its fluctuating motion. In agreement with observations by *Winterhalter et al.* [1994] at 1 AU, the plasma sheet thickness is much larger than that of the embedded current sheet. The plasma sheet is characterized by depressed magnetic field intensity and proton temperature, enhanced values of β (thermal to magnetic pressure ratio), and weakly varying total pressure, although departures from these conditions may occur. An extended density halo appears to surround the plasma sheet.

Finally, we would like to comment briefly on the helium content at the plasma sheet. As well established by *Borrini et al.* [1981] and *Gosling et al.* [1981], the relative helium abundance inside the plasma sheet is appreciably lower than outside. These results have been obtained at hourly scale. With 81-s Helios data we can look in much greater detail at such behavior. Figure 4 displays the proton density N (solid line) and the relative helium abundance N_α/N (dots) for the period shown in Figure 3. Also at our small scale a strict relation between helium abundance and plasma sheet is found, with a suddenly decreasing helium content as soon as the plasma sheet is entered (see, for instance, the N and N_α/N behavior around CL 263). Unfortunately, due to

an insufficient coverage of helium data a similar study for the near-the-Sun periods of Figures 1 and 2 cannot be done.

Comparison with radio occultation measurements of coronal streamers

Although it has been known for some time that the heliospheric plasma sheet is associated with coronal streamers observed in white-light measurements (see *Gosling et al.* [1981]), details of this connection have been elusive because of the lack of solar wind measurements inside 0.3 AU. Recent progress in probing coronal streamers near the Sun with radio occultation measurements has improved this situation considerably. Path-integrated measurements of density, density fluctuations, and magnetic field inferred from these measurements show that the stalks of coronal streamers have the same features as the heliospheric plasma sheet. With an angular size of 1-2 degrees, stalks of streamers envelope the heliospheric current sheet [*Woo*, 1997]. They comprise strong fine-scale filamentary structures, and path-integrated density increases by a factor of about two across them [*Woo et al.*, 1995]. The stalk of the coronal streamer observed in white-light measurements is, therefore, the coronal counterpart of the heliospheric plasma sheet.

The radial evolution of the streamer stalk observed by the remote sensing radio occultation measurements [*Woo et al.*, 1995] is consistent with that of the heliospheric plasma sheet observed by Helios, with the exception of the $\delta N/N$ behavior. As shown in the previous section, Helios high-time resolution measurements of $\delta N/N$ do not exhibit any relevant enhancement at the plasma sheet. This does not agree with the enhancement in relative amplitude of the small-scale fluctuations of the path-integrated density observed in streamers near the Sun, and also with the behavior of $\delta N/N$ seen by both Helios and other spacecraft [*Huddleston et al.*, 1995] at larger (hourly) scale.

This result could be real, but other causes may be differences between point and path-integrated measurements or sensitivity of the plasma analyser.

The strikingly abrupt boundaries of the streamer stalks containing the enhanced fine-scale structures near the Sun suggest that these boundaries separate two kinds of solar wind. That the high-time resolution measurements of relative helium abundance by Helios indicate decreases in helium abundance coinciding with the plasma sheet boundaries even at 1 AU reinforces the notion that the solar wind within the stalk is a different kind of solar wind (with different solar origins) than that outside it.

Finally, recent comparisons between simultaneous radio occultation measurements of the solar wind near 30 solar radii and white-light measurements of the solar corona indicate that, apart from the narrowing of streamers to stalks prior to their eventual radial expansion beyond the inner corona, coronal structures observed in white-light near the Sun extend radially into interplanetary space [*Woo and Habbal*, 1997]. The halo surrounding the plasma sheet appears to represent the radial extension of the boundaries of the streamer near the Sun before it narrows to a stalk farther away. This effect is also evident in the recent SOHO white-light measurements of coronal streamers out to 20 solar radii [*Brueckner*, 1996], and the Helios measurements indicate that the halo persists at least up to 1 AU.

Concluding Remarks

The structure of the heliospheric plasma sheet near 0.3 AU (Helios observations) is similar to that near 1 AU (Helios observations and paper by *Winterhalter et al.*, 1994). In particular, amplitude and angular width of the density enhancement do not change significantly.

When these results are compared with radio occultation measurements of coronal streamers near the Sun, it is clear that the stalks of coronal streamers are the coronal counterpart of the plasma sheet. Since the stalks of coronal streamers may be a relevant

source of slow solar wind, investigations of the heliospheric plasma sheet could lead to an improved characterization of the slow wind.

In summary, beyond 0.1 AU the heliospheric plasma sheet appears to be a permanent density structure that expands with the solar wind without significant evolution.

Finally, we would remark that from our analysis for the first time white-light, radio occultation, and in-situ plasma measurements appear all connected by a single common feature (and apparently the strongest feature in the background solar wind), a feature that may serve as a fiduciary (reference point) for any future comparisons of these diverse but extensive data sets.

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Figure Captions

Figure 1. Solar wind parameters (see text for detailed list) versus Carrington longitude for HCS observations near 0.3 AU.

Figure 2. Solar wind parameters, in the same format as Figure 1, for a HCS observation near 0.4 AU.

Figure 3. Solar wind parameters, in the same format as Figure 1, for HCS observations near 0.9 AU.

Figure 4. Proton density (solid line) and relative helium abundance (dots) versus Carrington longitude for the interval shown in Figure 3.

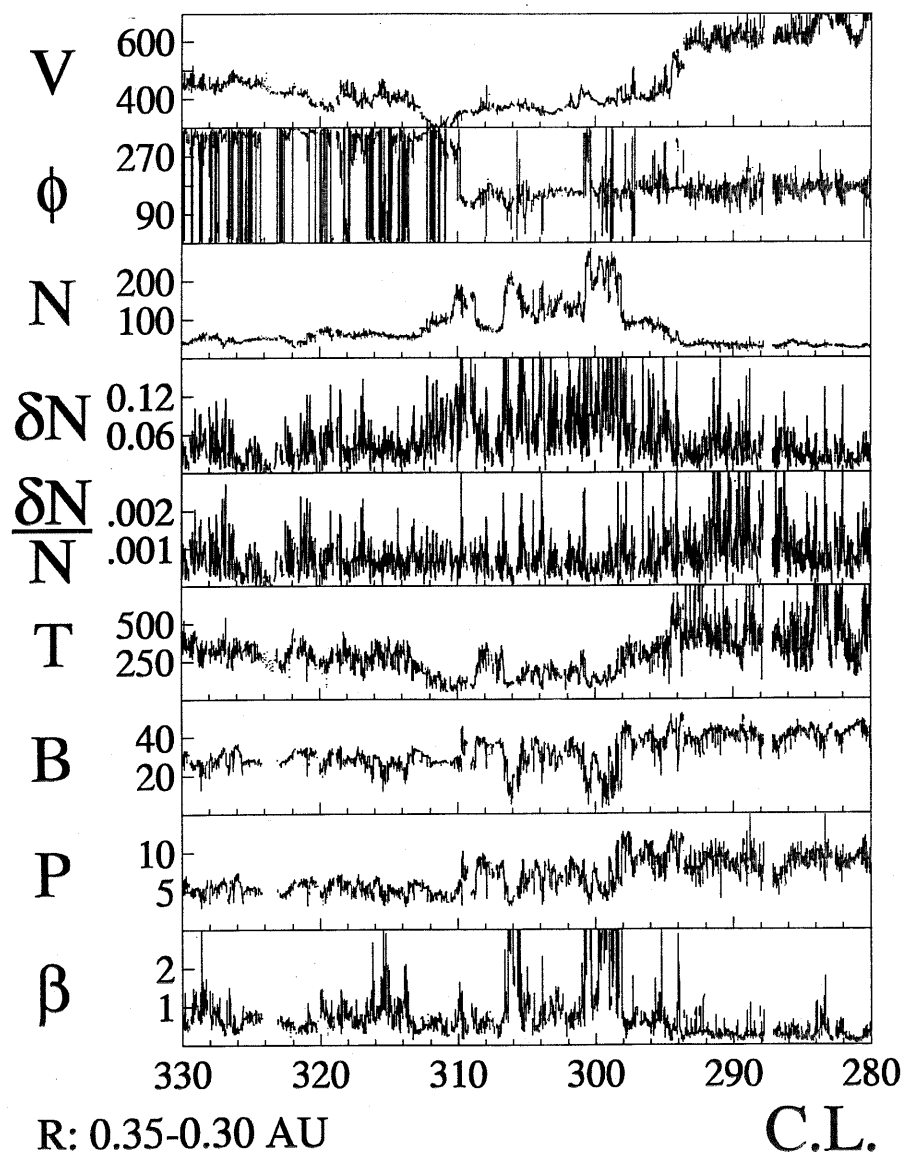


Fig- 1

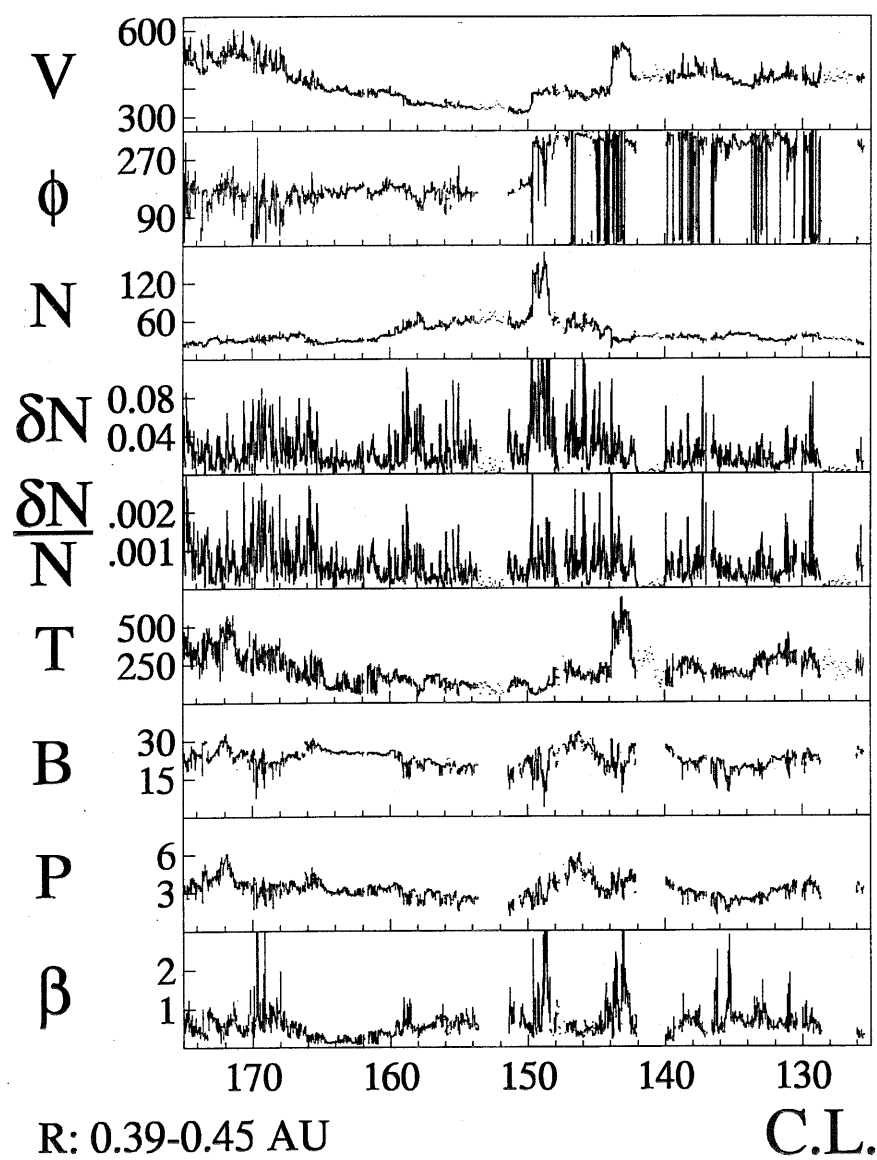


Fig. 2

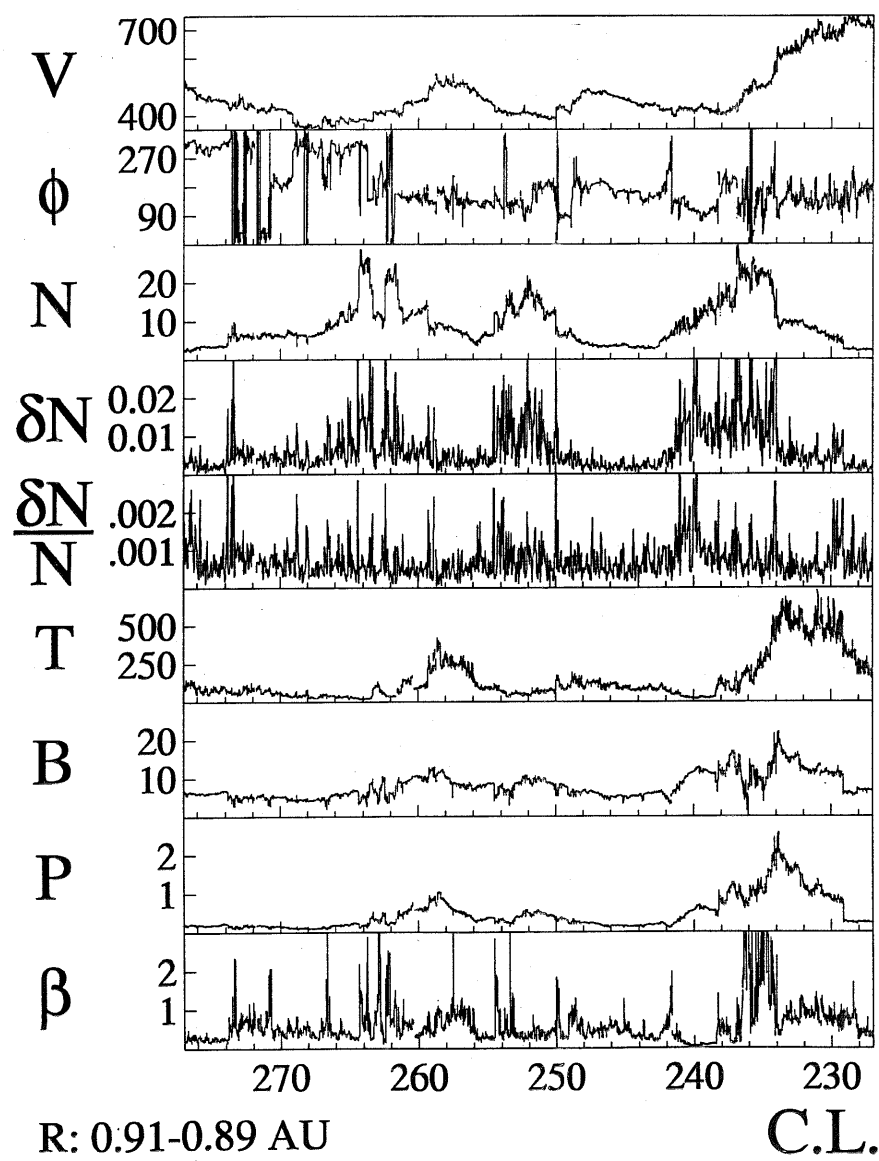


Fig. 3

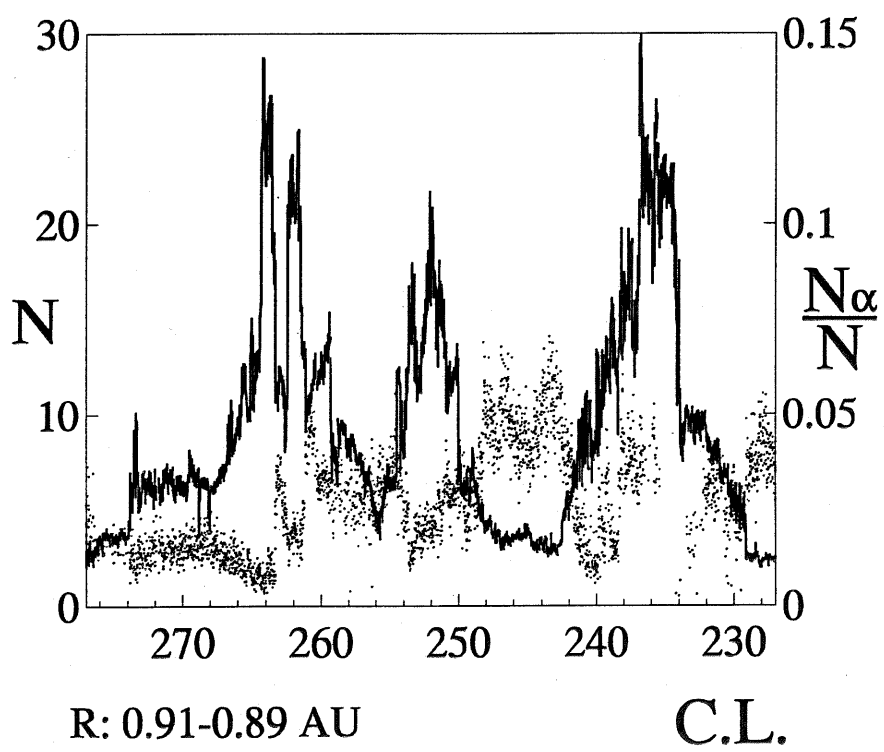


Fig. 4